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Summary of major research findings in three topical areas: 1) traveling wave concepts in the dynamics and control of Large Space Structures, 2) passive damping in Large Space Structures Applications, and 3) active control of rigid and flexible Manipulator Arms. The traveling wave concepts for characterizing the dynamics of flexible structures have introduced an alternative to modal synthesis and established a basis for the development of new controls algorithms. Passive damping studies identified various types of damping mechanisms including thermoelastic, and electromagnetic, and quantified their relative contributions. The active control studies generated a number of algorithms and control strategies and demonstration applications.

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- 22b. TELEPHONE (Include Area Code): (202) 767-4937
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STANFORD UNIVERSITY
Department of Aeronautics and Astronautics
William F. Durand Building
Stanford, California 94305

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Dr. Anthony Amos
AFOSR/NA
Building 40, Room A227
Bolling Air Force Base
Washington, D.C. 20332

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Publications, Personnel and Related Activities

Research activity under the subject grant completed the customary five years and was brought to a close on December 15, 1986. This Final Report is somewhat overdue because the Principal Investigator was overburdened with teaching and administrative duties during Stanford's Winter and Spring Quarters, along with a natural reluctance to recognize the irreversible end to a long and productive association with an important Air Force program.

Four previous Interim Scientific Reports, as well as the annual renewal proposals which were submitted on the grant, have provided considerable detail - as of their respective dates - about the various research projects which have been conducted. An unusually large number of publications, many of them now in the archive literature, can be attributed to the grant. Accordingly, it would be redundant to furnish large quantities of technical material in the present summary, which is designed primarily to meet an administrative requirement of the contract between AFOSR and Stanford. What will be done, under a series of major "themes" that constitute foci of the five year's work, is to give brief descriptions of principal contributions, mention the responsible individuals, and list all publications known to the Principal Investigator.

Five Stanford doctorates have been earned with partial or full support from the grant. Drs. Douglas Bernard, Andreas von Flotow, Usik Lee, Donald Edberg and Elke Meier Gayle are now variously employed in academia, industry and research laboratories. In general one can say that their present activity builds in significant ways on their Stanford research. In most cases, it is also contributing to the national aerospace effort and, more specifically, to USAF goals involving the applications of large space structures. For example, von Flotow is Assistant Professor of Aeronautics and Astronautics at Massachusetts Institute of Technology, where he works, teaches and publishes in the fields of structural dynamics, aeroelasticity and active control. Dr. Edberg is on the staff of Jet Propulsion Laboratory, responsible for experimental studies on active control of flexible structures. Dr. Gayle heads a satellite control-system development group at Ball Brothers, with design objectives related to the S. D. I. program. Dr. Lee, incidentally, recently received a faculty appointment in his native Republic of Korea. He will be training young aerospace engineers for service in one of the United States' staunchest allied countries in Asia.

It is also worth noting that numerous seminars and paper presentations have stemmed from OSR-supported research. In particular participants have interacted with the aerospace community through various meetings sponsored by AIAA. There have been grant-related presentations at each of the last five AIAA et al. Structures, Structural Dynamics and Materials Conferences, together with back-to-back Dynamics Specialist Meetings. At the April 1987 28th "SDM Conference" in Monterey, CA, the Principal Investigator was invited to chair a technical session and was also a member of a panel discussions on Aerospace Education. During the past five years there have been all manner of opportunities for informal contacts with aerospace engineers, during which information has been exchanged about findings under the project.

Finally, the subject of awards is worth noting. At the 27th "SDM Conference" in San Antonio, TX, two doctoral students from the Stanford group were presented with checks plus pewter engraved Jefferson Goblets for outstanding papers. Two weeks ago the Principal Investigator was notified by the president of the German aerospace professional society, DGLR, that he will be the 1987 recipient of the Ludwig-Prandtl-Ring for a lifetime of contributions to the fields of aeroelasticity and unsteady aerodynamics. This award and the associated gold finger ring will be presented at DGLR's annual meeting in Berlin on October 5, 1987. Two years ago the co-Principal Investigator, Prof. A. E. Bryson, Jr., received from ASME the Rufus Oldenburger Award - the highest recognition given by that society for research in the field of active control.

Traveling Waves, Dynamics and Control of Large Space Structures (LSS)

In early phases of grant research, support was given for completion of the PhD thesis of Dr. Bernard (Ref. 1), which was one of Stanford's first contributions to the subject of active control of large, flexible structures. His advisor, Prof Bryson, has also presented and published several papers on this subject, of which Ref. 2 is typical.

The Principal Investigator developed an ongoing interest in the dynamics of LSS, with emphasis on the devlopment of suitable analytical descriptions of the "plant" for purposes of active control-system design and on the possible transfer to space vehicles of methods useful for modeling large, flexible aircraft in the earth's atmosphere. He stimulated Dr. von Flotow to undertake research centered on the traveling-wave approach to LSS dynamics, which ultimately resulted in an outstanding doctoral dissertation (Ref. 3). The publications flowing from this activity and from von Flotow's ongoing work on this and related subjects at Stanford, at DFVLR Oberpfaffenhofen in FRG and at MIT are almost too numerous to list. References 4 through 10 are typical examples. It can be stated, without exaggeration, that this man's influence on the understanding of LSS dynamics has been as great as that of any other single individual during the past five years.

Along with Professor E. Crawley of MIT, Professor L. Meirovitch of VPISU and others, the Principal Investigator has been called upon to advise NASA and other federal agencies regarding R.&D. activity relevant to LSS. One interaction of this kind gave rise to the investigation which resulted in Ref. 11.

Passive Damping in Materials and Structures Suitable for LSS Application

Another topic which aroused the Principal Investigator's interest in the early 1980's was the possibility of predicting the inherent energy-dissipation characteristics of structures and materials under dynamic excitation. A review of the various possible mechanisms contributing to this phenomenon led to the identification of thermoelastic damping as the most universal mechanism and one that might be expected to set lower bounds for what would occur in practice.

The results of these early studies were delivered at an AIAA meeting and ultimately published as Ref. 12. A certain amount of consternation was produced in the damping research community, whose emphasis was on active damping and the development of special materials and systems for augmenting it, by the idea that inherent dissipation in a structure might often be adequate for purposes of control except in the presence of large, rapid disturbances.

In any event, this thread of damping studies resulted in both theoretical and experimental doctoral research by students in the Stanford group. Dr. Lee completed in 1984 (Ref. 13) a comprehensive and very scholarly study of two interesting damping mechanisms: thermoelastic and electromagnetic. The former showed that considerably larger critical ratios might be expected in structures involving flexural deformation of two-dimensional elements like plates and shells than in one-dimensional, beam-like configurations. The latter concluded that ferro-magnetic materials like steel alloys might be able to furnish substantial dissipation, but only in the presence of imposed magnetic fields. Hence the LSS application has limited promise. Lee's work has subsequently been presented and published in Ref. 14, among other places.

With help from Boeing Aerospace Company, which supplied several plate and beam specimens of various composite materials, Dr. Edberg carried out and described in the dissertation (Ref. 15) a very original laboratory study on the modal damping of typical aerospace structural systems. He was also indebted to Prof. Harris of MIT for the loan of two aluminum beams which were also tested. It is regretted that space limitations here prevent a full description of Edberg's research methodology and results. In a large vacuum chamber supplied by NASA Ames Research Center he launched a large number of specimens repeatedly and conducted what are probably the most precise measurements in history of critical damping ratios associated with vibration in their lower free-free natural vibration modes.

Two of Edberg's many findings perhaps deserve special mention. On an aluminum beam, he accurately verified the theory of "aerodynamic damping." He showed that it could be three or four times as large as that inherent in the structure, thus emphasizing the necessity of tests in vacuum facilities relevant to LSS design. Secondly, he discovered for several plate specimens that measured critical ratios are two or more times what might be expected on the basis of theory (e. g., Ref. 13). This discrepancy is believed to be a significant one, and it has not yet been explained by students of the subject. Typical publications based on Ref. 15 will be found in Refs. 16-18, the last of which describes follow-on work on thermal control of vibration which he performed while at JPL.

Control of Rigid and Flexible Manipulator Arms

In the Guidance and Control group of Stanford's Department of Aeronautics and Astronautics, under the leadership of Department Head R. H. Cannon, Jr., there has existed since the early 1960's a tradition on research on active control of flexible beams and other elastic structures. Recently this has moved toward application in two fields: robotics and space systems. Some of the latter is relevant to LSS as such, whereas other portions deal with manipulator arms typified by the Space Shuttle RMS.

Building on the basic methodology developed by Weinreb (Ref. 19) and recently with grant support supervised by Prof. Bryson, Dr. E. B. Meier (now Gayle) completed an investigation (Ref 20) concerning such manipulators. Her subject was the adaptation of optimal analysis of robots with rigid links to cover the more realistic case of flexible members. The objective was to bring about minimum-time displacement of the robot's tip from one position to another within its range of operation. It was found that in practical cases so-called "bang-bang" operation of the robot's joint torques yields performance essentially as good as what can be achieved with (much more analytically-complex) continuous variation of these torques. Thereby a great simplification is achieved in carrying out the opitimization.

Reference 20 describes an algorithm which is a modification of the steepest-descent method used in optimal programming. The algorithm assumes that the controls are always at their bounding values and finds the times at which they must switch from one bound to the other in order to find the best solution to the minimum-time problem. A distinguishing feature is that variations in the control are considered only at discrete times - the nominal switch times.

The new algorithm was applied to a two-link arm with two torque control inputs. Exact control switch times were found for a large number of repositioning maneuvers. Of special interest was the discovery that the minimum time reaches a sort of "plateau" when the translation approaches the limits of the arm's operating range. The algorithm was further extended to include open initial conditions, and full specifications were prepared for generalizing the methodology to flexible, two-link robot arms. This last would have become the subject of a new doctoral research project had OSR support been continued beyond the five-year period.

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